UNIVERSITÉ DU QUÉBEC À MONTRÉAL

THE IMPACT OF DAMS ON THE SAINTE-MARGUERITE AND ROMAINE RIVERS ON THE PHYTOPLANCTON COMMUNITIES AND THE PHYSICAL-CHEMICAL PROPERTIES OF THEIR ESTUARIES

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IMPACT DE L'HARNACHEMENT DES RIVIÈRES SAINTE-MARGUERITE ET ROMAINE SUR LES COMMUNAUTÉS PHYTOPLANCTONIQUES ET SUR LES PROPRIETÉS PHYSIOCHIMIQUES DANS LEURS ESTUAIRES

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PAR
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TABLE DES MATIÈRES

LISTE DES FIGURES ET TABLEAUX

RÉSUMÉ

Depuis les dernières décennies, l'hydroélectricité est devenue une source majeure d'électricité pour le Québec, tout en représentant une source importante d'exportation d'énergie pour cette province canadienne. Malgré le fait qu'il est de plus en plus évident que toutes les formes d'électricité ont des répercussions environnementales, les impacts cumulatifs des grands barrages hydroélectriques du nord ne sont pas bien étudiés. Il y a encore de grandes quesions à aborder, particulièrement concernant les effets cumulatifs et à long terme sur les écosystèmes estuariens. Les rivières Romaine et Sainte-Marguerite se situent sur la côte-nord du Québec, et tandis que la rivière Sainte-Marguerite est déjà harnachée, des barrages sur la rivière Romaine sont présentement en construction. Les deux rivières coulent directement dans le golfe du Saint-Laurent, un écosystème marin ayant une diversité animale et végétale importante. En utilisant deux approches différentes, les études de laboratoires et les images satellites, l'objectif de cette étude était de déterminer les impacts des barrages hydroélectriques sur les écosystèmes marins. Au laboratoire, notre but était de déterminer comment le taux de croissance et la photosynthèse de deux espèces de phytoplancton d'eau douce retrouvées dans l'estuaire de la rivière Romaine sont affectés par les changements de salinité et de température. Avec l'aide d'images satellites provenant du Landsat-TM5 bande 6 et les images SeaWiFS, il a été possible d'approfondir nos connaissances quant aux changements entraînés sur l'estuaire par le barrage de la rivière Sainte-Marguerite, avant et après la mise en eau en 1998. Le taux de croissance et la photosynthèse d'Ankistrodesmus falcatus et Fragilaria crotonensis ont été affectés par une augmentation de salinité. Le taux de croissance a diminué linéairement avec l'augmentation de la salinité et une diminution significative du rendement photochimique (Φ'_M) a été observé en fonction de ce dernier. La température de l'eau a aussi affecté le taux de croissance ainsi que la photosynthèse, et une interaction a été notée entre la salinité et la température. Ces résultats ont été corroborés avec les images satellites. Dans le cas de la rivière Sainte-Marguerite, nous avons déterminé que la superficie du panache diminue linéairement en fonction des débits de la rivière. En plus, il y avait une différence significative entre la biomasse de phytoplancton dans l'estuaire avant et après la construction du barrage. Les résultats suggèrent que les répercussions environnementales peuvent être importantes parce que les débits d'eau douce qui arrivent dans le golf du Saint-Laurent ont déjà diminué à cause des barrages hydroélectriques.

Mots-clés: photosynthèse, salinité, température, fluorescence, estuaries, A. falcatus, F. crotonensis, rivière Sainte-Marguerite, rivière Romaine, hydroélectricité, Landsat-TM5, SeaWiFS, production primaire

ABSTRACT

Overtime, hydroelectric power has become the major energy source for Quebec, as well as a major energy export for this Canadian province. While it is becoming increasingly evident that all energy sources have environmental impacts, the repercussions of extensive large-scale hydroelectric developments in northern settings are less clear. Specifically, it remains unclear if there are cumulative long-term effects on estuarine ecosystems. The Romaine and Sainte-Marguerite Rivers are both situated on Quebec's North Shore, and while the Sainte-Marguerite already has a hydroelectric dam, those on the Romaine River are currently under construction. Both rivers flow directly into the Gulf of Saint-Lawrence, a marine ecosystem. Using two different techniques, laboratory studies and satellite imaging, the objective of this study was to determine what impacts hydroelectric dams may have on marine ecosystems. In the laboratory our goal was to determine how the growth and photosynthesis of two freshwater algal species found in the Romaine River estuary are affected by changes in the water temperature and salinity. With the use of Landsat-TM5 bandwidth 6 and SeaWiFS images, it was possible to further explore how a dam on the Sainte-Marguerite River may have affected its estuary. Images were used from before and after 1998 when the reservoir began filling. According to laboratory results, growth rate and photosynthesis was affected for species Ankistrodesmus falcatus and Fragilaria crotonensis. Growth rate decreased linearly as a function of increasing salinity and a marked decrease was noted for operational quantum yield as salinity increased. Temperature also affected growth and photosynthesis and there was an interaction between salinity and temperature. Laboratory results corroborated findings from satellite images where it was determined that river plume surface area decreases linearly as river flow decreases. Furthermore a significant difference between primary production in the estuary was noted before and after the construction of the dam. Results are alarming as the environmental repercussions could be important because freshwater flow to the Saint-Lawrence watershed has been drastically altered over the last century by numerous hydroelectric dams.
Keywords: Photosynthesis, salinity, temperature, fluorescence, estuaries, A. falcatus, F. crotonensis, Sainte-Marguerite River, Romaine River, hydroelectricity, Landsat-TM5, SeaWiFS, primary production

CHAPTER I

GENERAL INTRODUCTION

1.1 Introduction

Over time, hydroelectric power has become the major energy source for Quebec, as well as a major export for this Canadian province. While it is becoming increasingly evident that all energy sources have environmental impacts, the repercussions of extensive large-scale hydroelectric developments in northern settings are less clear. The scientific community has achieved a better understanding of the effects of mercury contamination (Montgomery et al., 2000; Hall et al., 2005; Bodaly et al., 2007), greenhouse gas emissions (Soumis et al., 2005; Oelbermann and Schiff, 2010; Weissenberger et al., 2010) and biodiversity loss (McAllister et al., 2001; Lopez-Pujol and Ren, 2009) that result from dam construction. Furthermore, social consequences of dam development on local populations have been examined (Rosenberg et al., 1997). However, it is still unclear if dams affect phytoplankton communities in estuaries and if there are any cumulative long-term effects on larger marine ecosystems.

1.2 Problematic

As a result of hydroelectric dams the flow of fresh water that reaches estuaries arrives at different times of the year and under different conditions (Bunn and Arthington, 2002, Gough et al., 2005). Hydroelectric developments on northern rivers trap high-spring flows in order to fill reservoirs and release higher-than-normal flows in winter when power is needed (Rosenberg et al., 1997). Consequently, runoff is transferred from the biologically active period to the biologically inactive period of the year (Neu, 1976; Rosenberg et al., 1997). In northern Quebec, this means that the spring floods that normally occur during late May and early June are lessened and do

not bring large quantities of freshwater into estuaries. A need exists to study the cumulative impacts of altered flow regimes on marine ecosystems, particularly the effects to phytoplankton communities and the impacts to the physical and chemical properties of estuaries downstream of hydroelectric dams.

Altering flow regimes is of particular importance because freshwater inflow is one of the most influential factors affecting phytoplankton community structure and function in estuaries (Sklar and Browder, 1998). Altering freshwater inflow changes the physical and chemical properties of an estuary by altering the interface between river and marine ecosystems. As a result of decreasing freshwater inputs into marine ecosystems, marine salt water is able to encroach further upstream, resulting in higher than normal salinity concentrations, lower water temperatures in estuaries and smaller plume surface areas. In fact, it has been estimated that the Gulf of Saint-Lawrence exhibits higher than normal salinity levels during the spring because of the number of hydroelectric dams on rivers that flow into this watershed (Neu, 1976). Along Quebec's North Shore, spring runoff from rivers normally occurs towards the end of May or the beginning of June. Higher river runoff can be responsible for higher densities of phytoplankton, zooplankton and fish larvae in river plumes and estuaries (Sutcliffe, 1973; Grimes and Kingsford, 1996).

Phytoplankton are an important tool for the study of environmental change. Generally, these single-celled algal species are more susceptible to changes in water chemistry and can thus act as alarms to environmental change (Freedman, 2000). Furthermore, phytoplankton play a key role in estuary ecosystems. Estuaries, along with coral reefs, have particularly high concentrations of particulate organic matter (POM) and productive food webs (Martineau et al., 2004). In the Gulf of Saint-Lawrence, phytoplankton are the primary producers who make food available to other trophic levels, thus ensuring a flow of energy that moves up the food chain to tertiary consumers (Day et al., 1989; Martineau et al., 2004). Not only do phytoplankton play

an integral ecological role in promoting biological diversity, they also play an important economic role as food for species that make up the bulk of commercial fisheries (Mallin and Paerl, 1994). By developing a better understanding of effects to phytoplankton communities, we can begin to understand how hydroelectric dams may affect the entire food web.

1.3 Impact of hydroelectric dams on estuaries

In order to understand the repercussions of hydroelectric dams on marine ecosystems, it is necessary to first examine how these dams alter the physical and chemical properties of their estuaries. For the purpose of this study, the Romaine and the Sainte-Marguerite Rivers were examined.

The Romaine River on Quebec's North Shore provides a valuable case study as this river drains into the Mingan Archipelago National Park, an important biologically diverse ecosystem (Figure 1.1). Unique geological conditions, coupled with heavy inputs of freshwater from the Romaine River, contribute to the park's biodiversity. While the Romaine River is presently a free flowing river, construction of four dams began in May 2009.

Nearly 250 kilometers east of the Romaine River is the Sainte-Marguerite River, located near the town of Sept-Iles (Figure 1.2). The Sainte-Marguerite Three (SM3) hydroelectric complex was built during the 1990's. Prior to the construction of the dam, it was estimated that the flow of the Sainte-Marguerite River during the spring floods of May and June was between 321.6m^3/s and 364m^3/s (Hydro-Québec, 1991). Hydro-Québec predicted that reservoir filling would start during May 1998 and would take up to 40 months. During this time, it was predicted that the flow of the Sainte-Marguerite River would be reduced to 20-35% of its original volume. Once the dams became operational, the flow would remain reduced, between 14 and

44% of its original volume during the biologically active period of the year (April to October).

As a result of hydroelectric development on the Romaine River, the input of freshwater to the estuary will be reduced during May and June. Therefore, it is predicted that salinity in the estuary should increase in the spring (Hydro-Québec, 2007).

In addition to changing chemical properties of an estuary, dams also alter physical properties such as water temperature. According to Hydro-Québec's environmental impact assessment for the Sainte-Marguerite Three SM3 hydroelectric complex, average water temperature in the estuary would decrease as a result of the dam (Hydro-Québec, 1991). On average, throughout the year, water from North Shore rivers is warmer than that of the Gulf. As freshwater inputs decrease in estuaries as a result of reservoir filling, temperatures likely decrease, as estuaries are more heavily influence by the Gulf waters.

It is essential to consider the combined effects of salinity and water temperature as these two environmental factors will vary simultaneously as a result of changing freshwater inputs into the estuary. Presently, the combined effects of salinity and temperature on phytoplankton are not well understood.

1.4 Impact of physical and chemical changes on phytoplankton

According to Hydro-Québec's (1991, 2007) environmental impact assessment for both the SM3 and the Romaine hydroelectric complexes, there would not be a significant change to primary productivity associated with the changes in the estuary. The environmental impact assessments did not measure the surface area of the river plumes or how those regions would be reduced when river flow decreased. Furthermore, the impact assessments considered total phytoplankton biomass and did

not consider how individual species would react differently to the physical and chemical changes occurring in the estuaries.

According to Segal et al. (2006) and Azevedo et al. (2008), primary productivity decreases with an increase in salinity. Both studies, conducted *in situ*, demonstrated a decrease in dissolved oxygen and chlorophyll *a* in samples collected along an increasing salinity gradient. A decrease in the ratio of photosynthesis and respiration to biomass was noted along an increasing salinity gradient, demonstrating that phytoplankton species show symptoms of stress when salinity increases (Segal et al., 2006). Salinity can act as a toxin for freshwater algae and salinity has been suggested as one of the major constraints on species diversity and on the productivity of natural populations of algae in estuaries (Bartolomé et al., 2009).

It is predicted that long-term changes in water temperatures in estuaries have already altered biological processes, such as spawning and the size of larvae and eggs amongst fish populations, in the Saint-Lawrence watershed (Lillelund, 1964; Neu, 1976). Changes in water temperature may also affect phytoplankton growth and photosynthesis. Algal species are adapted to given temperature ranges and as a result decreases in water temperatures can cause rates of photosynthesis to decrease (Davison, 1991). Temperature changes can alter membrane fluidity by altering the fatty acid composition, thus affecting the efficiency of photosynthesis (Raven and Geider, 1988; Henley et al., 2002). Henley and colleagues (2002) advanced that interactions exist between the affects of salinity and temperature as both have the ability to alter lipid concentrations.

1.5 Photosynthesis

In order to understand how phytoplankton cells may be affected by physical and chemical changes in the estuaries, we examined effects to photosynthesis. Photosynthesis is a biological process that converts light energy to chemical bond

energy that is stored as organic carbon compounds (Falkowski and Raven, 2007). In marine ecosystems, photosynthesis converts particulate organic matter and light energy and provides the primary source of organic matter for all other aquatic organisms (Falkowski and Raven, 2007). As a result, the ability of phytoplankton to perform photosynthesis assures energy transfer along the entire food web and is a major contributor to ecosystem health.

The process of photosynthesis by which light is captured and converted into chemical energy and produces oxygen molecules occurs in two phases: a photochemical phase called light-dependent reactions and a biochemical phase called light-independent reactions. The first phase, the light-dependent phase, involves the transfer of solar energy into reserves of adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH). During the second phase, the stored energy is used to convert atmospheric carbon dioxide into sugars. All of this activity takes part in chloroplasts (Taiz and Zeiger, 2006).

The light-dependent reactions occur in the thylakoid membrane of chloroplasts. During the light phase of photosynthesis, chlorophyll and other pigments in the light-harvesting antenna complexes of photosystem II (PSII) capture photons from light energy. When sufficient excitation energy is obtained, electrons are transferred through the electron transport chain, thus creating a chemiosmotic potential across the membrane that enables the synthesis of ATP. When a chlorophyll molecule captures light, it becomes excited and unstable due to this high-energy state. In order to dissipate energy and return to a stable-state, the molecule can either send an electron through the electron transport chain, send the energy to a neighboring molecule, dissipate the energy through heat or emit a photon. If the molecule emits a photon, this is called chlorophyll fluorescence and it represents a constant portion of energy captured by the light-harvesting antenna of PSII that cannot be converted into chemical energy. Through the use of pulse-amplitude

modulation (PAM) fluorometry, it is possible to measure fluorescence and develop an understanding of the efficiency of the photochemical processes occurring within algal cells.

Measuring dissipated fluorescence is a conventional tool in the study of the photosynthetic apparatus efficiency (Lavorel and Etienne, 1997; Juneau et al., 2001). The photosynthetic apparatus may be sensitive to variations in environmental factors such as metals, fertilizers, temperature and light (Raven and Geider, 1988; Samson and Popovic, 1988; Rijstenbil, 2005; Dai et al., 2008). Direct or indirect modifications in photosynthetic electron transport activity are reflected in fluorescence emitted by chlorophyll molecules (Juneau et al., 2007). Therefore, measuring fluorescence has been used as a method of evaluating the toxic effect of pollutants on algae (Samson and Popovic, 1988; Juneau et al., 2001). Furthermore, photosynthesis has consistently been used as an indicator of phytoplankton health when examining salt toxicity (Grzebyk and Berland, 1996; Hancke et al., 2008; Bartolomé et al., 2009; Boughalleb et al., 2009).

1.6 Satellite Images

In order to better understand what took place in the estuary of the Sainte-Marguerite River during the time of the spring run-off, Landsat-TM5 technology was used to map the estuary before and after the hydroelectric dam was built. Through the United States Geological Survey (USGS) Landsat-TM5 bandwidth 6 data can be downloaded. Band 6 has a wavelength of 10.40-12.50 micrometers and collects data at a resolution of 120 meters, which is then re-sampled to 60-meter pixels. Using thermal infrared technology, Landsat-TM5 band 6 data can be calibrated to provide sea surface temperature and can be used to better understand coastal water flow (Haakstad et al., 1994, Qin et al., 2001).

Additionally, through the use of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data, primary production can be monitored. SeaWiFS data, provided through Ocean Productivity at Oregon State University, provide net primary production estimates based on the Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski, 1997). Using the VGPM algorithm, net primary productivity is a function of chlorophyll, available light and the photosynthetic efficiency. Data is provided as milligrams of Carbon per sea surface area per day ($mgC \bullet m^{-2} \bullet day^{-1}$).

1.7 Objectives

By developing a better understanding of how freshwater phytoplankton react to potential changes in an estuary resulting from hydroelectric dams, in combination with a more in-depth analysis of changes incurred to the Sainte-Marguerite plume, it will become clearer what effects hydroelectric dams may have on marine ecosystems.

Our goal was first to determine how growth and photosynthesis of two freshwater algal species found in the Romaine River estuary are affected by concomitant changes in the water temperature and salinity. Secondly, with the use of satellite images, our objective was to determine if dams on the Sainte-Marguerite River have affected the surface area of the river plume and its phytoplankton biomass.

FIGURES

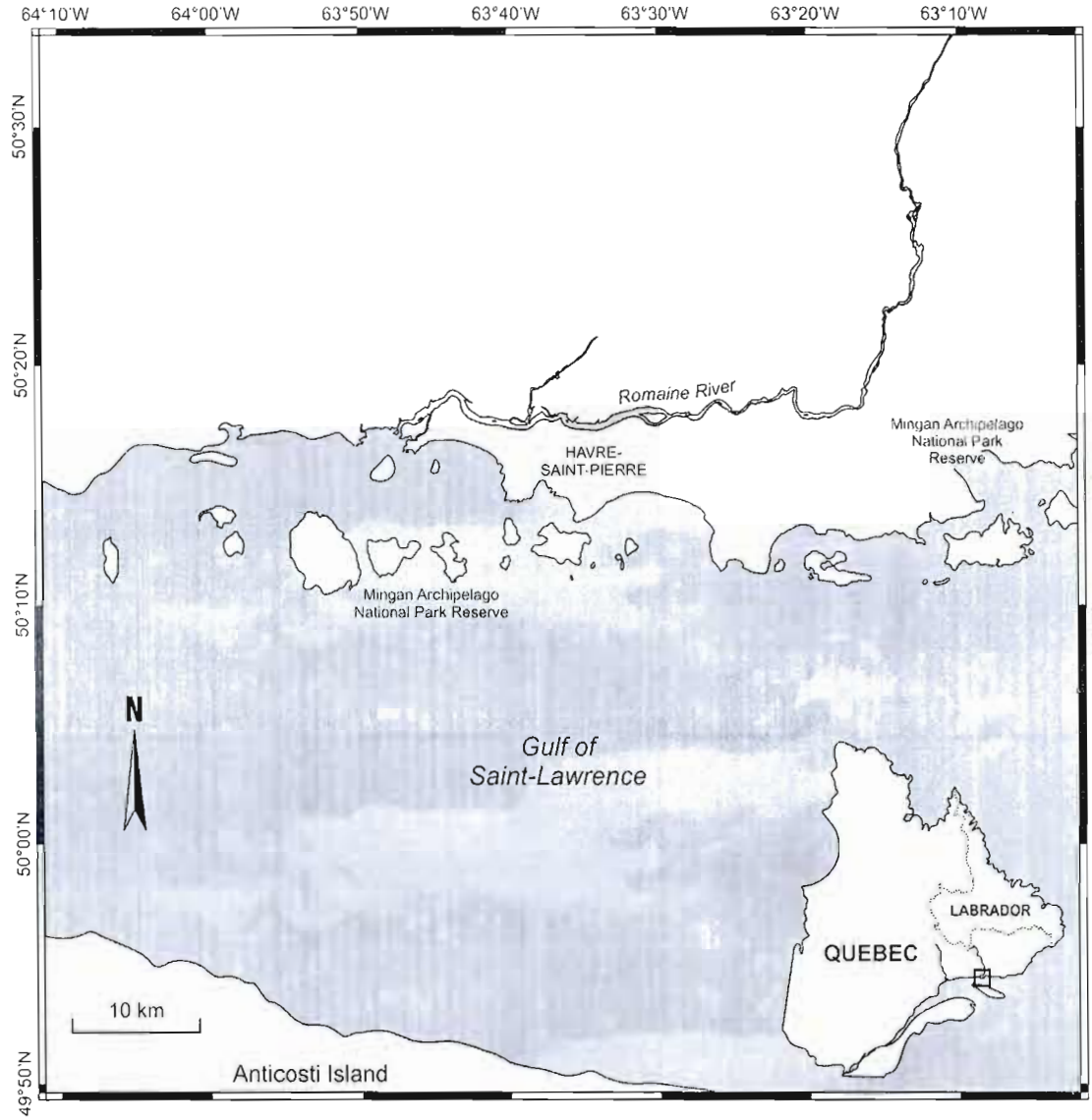

Figure 1.1: Romaine River and its estuary

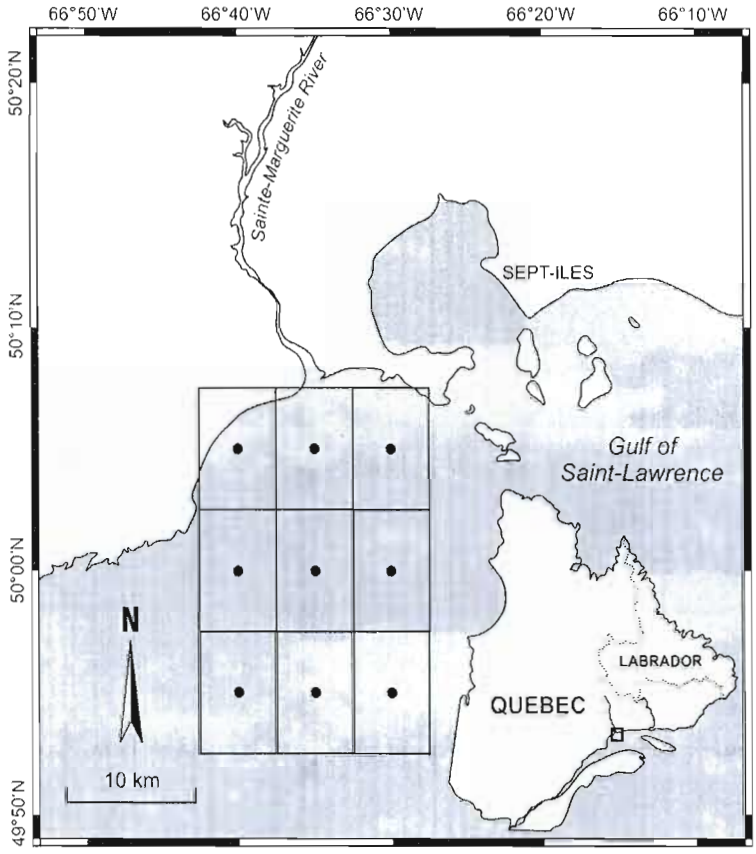

Figure 1.2: Sainte-Marguerite River and its estuary
*Grid marks individual pixels for SeaWiFS data

CHAPTER II

SCIENTIFIC ARTICLE

Effects of changing salinity and water temperature on the growth and photosynthesis of two freshwater phytoplankton, *Ankistrodesmus falcatus* and *Fragilaria crotonensis*

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Abstract

As a result of hydroelectric dams, the flow of freshwater to estuaries is transferred from the biologically active period of the year to the biologically inactive period. During the biologically active period of the year, salinity increases and water temperature decreases in estuaries downstream of dams, in comparison to non-dammed rivers. Phytoplankton growth is affected by such changes. Using *Ankistrodesmus falcatus* and *Fragilaria crotonensis*, two species of freshwater phytoplankton found in the Romaine River estuary, *in vitro* experiments were designed to test the effects of increasing salinity at different temperatures on growth and photosynthesis. Using growth rate and fluorescence as indicators of phytoplankton health, it is possible to determine that both species are negatively affected by increasing salinity, noted by decreasing growth rates and decreasing operational photosystem II quantum yield (Φ'_M). Results corroborate other studies conducted both *in vitro* and *in situ*, indicating that salinity acts as a toxin for freshwater phytoplankton. Environmental repercussions could be important, as freshwater flow to the Saint-Lawrence watershed has been drastically altered over the last century by numerous hydroelectric dams.

Keywords: Photosynthesis, salinity, temperature, fluorescence, estuaries, *A. falcatus*, *F. crotonensis*

2.1 Introduction

Over time, hydroelectric power has become the major energy source for Quebec, as well as a major energy export for this Canadian province. While it is becoming increasingly evident that all energy sources have environmental impacts, the repercussions of extensive large-scale hydroelectric developments in northern settings are less clear. The scientific community has achieved a better understanding of the effects of mercury contamination (Montgomery et al., 2000; Hall et al., 2005; Bodaly et al., 2007), greenhouse gas emissions (Soumis et al., 2005; Oelbermann and Schiff, 2010; Weissenberger et al., 2010) and biodiversity loss (McAllister et al., 2001; Lopez-Pujol and Ren, 2009) that result from dam construction. Furthermore, social consequences of dam development on local populations have been examined (Rosenberg et al., 1997). However, it is still unclear if dams affect phytoplankton communities in estuaries and if there are any cumulative long-term effects on larger marine ecosystems.

As a result of hydroelectric dams the flow of fresh water that reaches estuaries arrives at different times of the year and under different conditions (Bunn and Arthington, 2002, Gough et al., 2005). Hydroelectric developments on northern rivers trap high-spring flows in order to fill reservoirs and release higher-than-normal flows in winter when power is needed (Rosenberg et al., 1997). Consequently, runoff is transferred from the biologically active period to the biologically inactive period of the year (Neu, 1976; Rosenberg et al., 1997). In northern Quebec, this means that the spring floods that normally occur during late May and early June do not bring large quantities of freshwater into estuaries. Altering flow regimes is of particular importance because freshwater inflow is one of the most influential factors affecting phytoplankton community structure and function in estuaries (Sklar and Browder, 1998). Altering freshwater inflow changes the physical and chemical properties of an estuary by altering the interface between river and marine ecosystems. As a result of decreasing freshwater inputs into marine ecosystems, marine salt water is able to

encroach further upstream, resulting in higher-than-normal salinity concentrations and lower water temperatures in estuaries. In fact, it has been estimated that the Gulf of Saint-Lawrence exhibits higher-than-normal salinity levels during the spring because of the number of hydroelectric dams on rivers that flow into this watershed (Neu, 1976). In the Gulf of Saint-Lawrence, such alterations could affect marine biodiversity because zones where fresh water mixes with marine water are high in biological activity. Studies have demonstrated that higher inputs of freshwater correlate with higher densities of phytoplankton, zooplankton and fish larvae (Sutcliffe, 1973; Grimes and Kingsford, 1996). The Romaine River on Quebec's North Shore provides a valuable case study as this river drains into the Mingan Archipelago National Park, an important, biologically diverse, ecosystem (Figure 2.1). Unique geological conditions, coupled with heavy inputs of freshwater from the Romaine River, contribute to the park's biodiversity. As a result of hydroelectric development that began in 2009, the input of freshwater from the Romaine River will be reduced during May and June while reservoirs are refilling. Therefore, it is predicted that salinity in the estuary should increase in the spring (Hydro-Québec, 2007). According to Segal et al. (2006) and Azevedo et al. (2008), primary productivity decreases with an increase in salinity. Both studies, conducted *in situ*, demonstrated a decrease in dissolved oxygen and chlorophyll *a* in samples collected along an increasing salinity gradient. A decrease in the ratio of photosynthesis and respiration to biomass was noted along an increasing salinity gradient, demonstrating that phytoplankton species show symptoms of stress when salinity increases (Segal et al., 2006). Salinity can act as a toxin for freshwater algae and it has been suggested as one of the major constraints on species diversity and on the productivity of natural populations of algae in estuaries (Bartolomé et al., 2009).

In addition to changing chemical properties of an estuary, dams also alter physical properties, such as water temperature. According to Hydro-Québec's environmental impact assessment for the Sainte-Marguerite Three (SM3)

hydroelectric complex, water temperature in the estuary will decrease during the months of May and June as a result of the dam (Hydro-Québec, 1991). On average, throughout the year river water is warmer than that of the Gulf. As freshwater inputs decrease in estuaries as a result of reservoir filling, temperatures will likely decrease, as estuaries are more heavily influenced by the Gulf waters. It is predicted that long-term changes in water temperatures in estuaries have already altered biological processes, such as spawning and the size of larvae and eggs amongst fish populations, in the Saint-Lawrence watershed (Lillelund, 1964; Neu, 1976). Changes in water temperature may also affect phytoplankton growth and photosynthesis. Algal species are adapted to given temperature ranges and as a result decreases in water temperatures can cause rates of photosynthesis to decrease (Davison, 1991). Temperature changes can alter membrane fluidity by altering the fatty acid composition, thus affecting the efficiency of photosynthesis (Raven and Geider, 1988; Henley et al., 2002).

It is essential to consider the combined effects of salinity and water temperature as these two environmental factors will vary simultaneously as a result of changing freshwater inputs into the estuary. Henley and colleagues (2002) advanced that interactions exist between the affects of salinity and temperature as both have the ability to alter lipid concentrations, thus altering membrane fluidity. Presently, the combined effects of salinity and temperature are not well understood.

Our goal was to determine how growth and photosynthesis of two freshwater algal species found in the Romaine River estuary are affected by changes in the water temperature and salinity. Therefore, by developing a better understanding of how freshwater phytoplankton react to increasing salinity at different temperatures, the possible effects that hydroelectric dams may have on marine ecosystems will become clearer.

2.2 Methodology

Three samples of Romaine River water were collected from the estuary of the Romaine River on October 18th, 2009 when water temperature was comparable to that in the early spring (Hydro-Québec, 2007). Each sample contained approximately 500ml of water, taken from a depth of 20cm. For each sample, 10ml was removed and allowed to sediment in sedimentation towers for Utermöhl observation cuvettes. After which, samples were observed using a Leica inverse microscope, model DM IRB and phytoplankton species were identified. From the list of dominant species, *Ankistrodesmus falcatus* and *Fragilaria crotonensis* were selected because they were already growing well in the laboratory and because they belong to two different classes of phytoplankton (*Chlorophyceae* and *Bacillariophyceae* respectively). Freshwater species were selected for this study because they play an important role in marine ecosystems by adding to estuary biodiversity.

Stock cultures were grown in Bold's Basal medium (Stein, J. 1973) to which 290mg/l of $Na_2SiO_4 \bullet 9H_2O$ was added (BBM+Si). $Na_2SiO_4 \bullet 9H_2O$ was added to the medium because it is necessary for diatom growth. Cultures acclimated for 8 generations (approximately two weeks) to 15°C, 12°C and 9°C under constant irradiance of 110μmol photons m^{-2} s^{-1} with a light-dark cycle of 14:10h (combination of incandescent bulbs and fluorescent tubes Philips F72T8/TL841/HO). After which, cultures were exposed in triplicate to eight salinity concentrations over 72 hours (from 0 to 35 parts per thousand). Salinity was modified in BBM+Si by adjusting the quantity of NaCl in the medium. Biomass was monitored using a Turner Designs fluorometer, model TD-700 (Sunnyvale, USA), and growth rates were calculated from plots of the log of fluorescence versus incubation time. After 72 hours the effects of salinity on photosynthesis were measured using a WATER-Pulse-Amplitude-Modulated (WATER-PAM) fluorometer (Heinz Walz GmbH, Effeltrich, Germany). Maximal photosystem II quantum yield (Φ_M), operational photosystem II

quantum yield (Φ'_M), nonphotochemical quenching (NPQ) and relative unquenched fluorescence ($UQF_{(REL)}$) were calculated using the following formulas:

$\Phi_M = (F_M-F_O)/F_M = F_V/F_M$ (Kitajima et al., 1975) (Equation 1)

$\Phi'_M = (F'_M-F_S)/F'_M$ (Genty et al., 1989) (Equation 2)

$UQF_{(REL)} = (F_S-F'_O)/(F_M-F'_O)$ (Juneau et al., 2005) (Equation 3)

$NPQ = F_M/F'_M$ (Bilger and Björkman, 1990) (Equation 4)

After 72 hours, 20 ml of each culture were filtered using GF/F 1.2μm filters (Schleicher and Schuell, Whatman International Ltd., England) and stored at –80°C for chlorophyll extractions. Chlorophyll was extracted using 3ml of methanol and concentrations were measured using a spectrophotometer Cary300WINUV (Varian, USA) and calculated according to Lichtenthaler (1987).

Tukey-Kramer tests were calculated to test for significant differences at salinity=0, and linear regression analyses were done to determine the effect of salt on growth rate. Additionally, a covariance test and a heterogeneity of slope test were conducted to determine the interaction between salt and temperature. Tukey-Kramer tests were also conducted on all PAM parameters and pigment parameters to determine if significant differences existed. Non-linear tests were conducted to determine the Φ'_M median effective concentration (EC_{50}) values for both species at all three temperatures. EC_{50} values were only calculated for Φ'_M as it has been shown to be a better indicator of salt stress (Bartolomé et al., 2009). Probabilities are presented as significant ($p<0.05$), highly significant ($p<0.01$) and very highly significant ($p<0.001$). Statistical analysis was done using JMP 7.0.1 software (SAS Institute, NC, USA) and figures are presented using KaleidaGraph 4.1 software (Synergy Software, Reading, PA, USA).

2.3 Results

2.3.1 Growth Rates

Both *A. falcatus* and *F. crotonensis* species exhibited growth inhibition when exposed to increasing salt concentrations over 72 hours at all three temperatures. For *A. falcatus*, temperature influenced growth rate, demonstrated by the results of the Tukey-Kramer test where growth rates at salinity=0 were all significantly different (Figure 2.2). Average growth rates (doubling d^{-1}) at salinity=0 for 15, 12 and 9°C were 0.39, 0.29 and 0.17 respectively (where n=9). All mean growth rates were significantly different from each other. For *F. crotonensis* average growth rates for 15, 12 and 9°C were 0.15, 0.17 and 0.06 respectively. Mean growth rates at 12 and 9°C were not significantly different from each other but both were significantly different from the mean growth rate at 15°C (Figure 2.3).

According to a covariance test and a heterogeneity of slope test, an interaction exists for both species between salt and temperature (Table 2.1). According to individual tests between temperatures, *A. falcatus* displayed a significant difference between slopes at all temperatures, except between 15 and 12°C (Figure 2.2). In contrast, *F. crotonensis* displayed significant differences for all temperatures, except between 12 and 9°C (Figure 2.3).

2.3.2 Pigments

Pigment ratios (Chl *a*/Carotenoids, Chl *b*/Carotenoids, Chl *total*/Carotenoids) did not appear to change throughout the experiment and data were not significantly different, neither as a result of salinity nor temperature modifications (data not shown).

2.3.3 Phototsynthesis

Tukey-Kramer tests were done to compare PAM parameters at different salinities and at different temperatures. Results of tests between salinities demonstrated significant differences for all parameters except $UQF_{(REL)}$ and NPQ for *F. crotonensis*, where no significant difference was noted (Figure 2.4). Results are not shown for temperature as few significant differences were noted, indicating that selected temperatures did not affect PSII quantum yields (Φ_M and Φ'_M) for either *F. crotonensis* or *A. falcatus*.

Non-linear tests indicate that photosynthesis for all species, at all temperatures, is inhibited by an increase in salinity (Figure 2.5). For *A. falcatus*, Φ'_M EC_{50} values equaled 25.2 (24.0-26.8), 25.7 (25.6-27.0) and 18.8 (17.6-18.7) for 15, 12 and 9°C respectively. In contrast, Φ'_M for *F. crotonensis* appeared more sensitive to salt, with EC_{50} values of 19.4 (16.2-23.2), 20.8 (13.7-27.5) and 18.6 (15.2-21.6) for 15, 12 and 9°C respectively.

2.4 Discussion

According to our results, both phytoplankton species reacted to salinity stress at different concentrations, shown by differing negative slopes at all temperatures (Table 2.1) and by significant differences between growth rates at each salinity concentration. Our results support to previous studies that have shown that different phytoplankton species react differently to salt stress (Segal et al., 2006; Bartolomé et al., 2009). In fact, Bartolomé et al. demonstrated that growth inhibition can occur for cyanobacteria at a salinity concentration more than four times lower than those needed to inhibit green alga (2009). Segal et al. (2006), who conducted their experiments *in situ*, found there to be a progression from a plankton system to a benthic cyanobacterial mat system along an increasing salinity gradient.

For both species, our results demonstrated that growth rate was inhibited at salinity concentrations as low as 5 and 10 parts per thousand. While studies have

shown that salt affects phytoplankton growth rate (Grzebyk and Berland, 1996; Bartolomé et al., 2009), Boughalleb and colleagues (2009) suggested that growth rate is only affected by salt indirectly due to decreasing photosynthesis. Our results do not support this hypothesis because growth rate was inhibited at lower salinity concentrations than photosynthesis. The difference could be explained by the fact that Boughalleb et al. (2009) studied fodder plants, not algae, where growth can be attributed to other factors such as stomatal closure and water availability. Our results, however, agree with those of Bartolomé et al. (2009), who noted that a reduction of effective photosynthetic quantum yield induced by salt was time-dependent and higher than growth inhibition for *Dictyosphaerium chlorelloides*, a freshwater green alga. The EC_{50} for growth rate was 340mM (19.9 parts per thousand) and 357.8mM (20.9 parts per thousand) for effective photosynthetic quantum yield. While the authors did not note a significant difference between the two, the tendency appears to move in the same direction as our results. For both *A. falcatus* and *F. crotonensis* growth rates appeared to be more sensitive to salt, or were affected first, than photosynthesis evaluated by Φ_M and Φ'_M. Further work is needed in order to clarify why growth inhibition would be affected before photosynthesis under our conditions.

It has been shown that salinity stress in organisms alters biological processes such as photosynthesis and photorespiration (Azevedo et al., 2008; Bartolomé et al., 2009). It is evident that the photosynthetic apparatus was affected by increased salinity for both *A. falcatus* and *F. crotonensis* at all temperatures. EC_{50} values for Φ'_M ranged from 18.6 parts per thousand (for *F. crotonensis* at 9°C) to 25.7 parts per thousand (for *A. falcatus* at 12°C). According to Φ'_M EC_{50} values, the diatom *F. crotonensis* was more affected by salt than the green alga.

If algae were able to protect against excess energy arriving once the photosynthetic apparatus was damaged by salt, an increase in NPQ should be expected (Schindler and Lichtenthaler, 1997; Qiu et al., 2003; Boughalleb et al.,

2009). Neither *A. falcatus* nor *F. crotonensis* exhibited significant changes in NPQ values, indicating that neither species was able to protect against photodamage. It is possible that species were not able to adapt to increased salinity because our experiments lasted only 72 hours, in comparison to those conducted by Boughalleb et al. (2009), who were testing salinity effects on fodder shrubs, and seedlings grew for 2 to 3 months before photosynthetic activity was evaluated. The only significant change noted for NPQ was for *A. falcatus* at 12 and 9°C, although values appeared to decrease with an increase in salinity.

The observed decrease in Φ'_M can be attributed to a decrease in electron transport through the alteration by salt of the photosynthetic electron chain (Sudhir et al., 2005). Decreasing fluorescence, shown as a reduction in maximum photosystem II quantum yield, has been attributed to an inhibition of the electron flow at the oxidizing side of photosystem II (Lu and Vonshak, 2002). Bartolomé and collaborators (2009) first calculated 50% inhibition of photosynthetic yield and then grew two species under these conditions to determine time-dependent toxic effects induced by salt. After 72 hours they noted a decrease in oxygen production for both a green alga (*D. chlorelloides*) and a cyanobacterium (*M. aeruginosa*). Furthermore, the inhibitory effect induced by salinity stress on the photosynthetic apparatus was comparable to those caused by organic and inorganic pollutants (Pandard et al., 1993; Carrasco and Sabater, 1997). Therefore, we may advance that if salinity increases significantly in an estuary, salt may act as a toxic pollutant for both *A. falcatus* and *F. crotonensis*.

Growth rate declined rapidly with an increase in salinity for both species at all temperatures, but most markedly for the green alga, *A falcatus*, which is demonstrated by a more negative slope at all temperatures except 9°C, where *F. crotonensis* exhibited greater growth inhibition. In the case of *Prorocentrum minimum*, a toxic marine dinoflagellate, cells become encysted at temperatures below

10°C and growth rate decreased drastically (Grzebyk and Berland, 1996). It has also been suggested that temperature has had no effect on maximum quantum yield (Hancke et al., 2008). Our results reflect these findings as no significant difference was noted between Φ'_M and Φ_M at different temperatures when salinity was held constant.

In the case of hydroelectric dams altering the flow of freshwater to the estuary, water temperature and salinity will vary simultaneously (Hydro-Québec, 2007). As a result, it is essential to consider the combined effects of both environmental factors in order to understand how species will be affected by altered flow regimes. For both *A. falcatus* and *F. crotonensis*, there was an interaction between salinity stress and water temperature because growth rate was affected differently. The differences in temperature and how it affects salt toxicity may be related to energy that cannot be used reaching the photosynthetic apparatus. This excess energy, due to an over-reduction of reaction centers, may be harmful to photosystem II if it is not dissipated (Demmig-Adams and Adams, 1992; Foyer and Noctor, 2005). This might explain why *A. falcatus* was more affected by salt at 15°C than at 12 and 9°C (shown by a higher slope for the regression analysis of growth rate vs. salinity). The typical response for photosynthesis and growth rate is for it to increase progressively with increasing temperature until it reaches an optimal temperature, after which it decreases rapidly (Davison, 1991). It is possible that the 9°C could be the ideal growing condition for *A. falcatus*, although this is unlikely because other studies have demonstrated that *A. falcatus* can grow at temperatures as high as 22°C (Juneau, 2001). *F. crotonensis* was more affected by salt at 9°C than 12 and 15°C. In the case of *F. crotonensis*, our results corroborate Henley et al. (2002) who demonstrated that two species of chlorohytes (*Dunaliella* and *Nannochlori*) were more tolerant of high salinity at high temperatures, measured by the integrity of the light-harvesting system (77 K fluorescence emission spectra).

Studies have demonstrated that interactions exist between irradiance and salinity, which may clarify the temperature-salinity interaction. In the case of *P. minimum*, cells were unable to grow when salt levels were 5 parts per thousand at an irradiance of 250μmol photon m^{-2} s^{-1}, whereas growth occurred at the same salinity and an irradiance of 60μmol photon m^{-2} s^{-1} (Grzebyk and Berland, 1996). The authors found that a positive interaction existed, as low irradiance enabled cells to be more tolerant to low salinities.

If salinity increases in the estuary of the Romaine River, the growth and photosynthesis of *A. falcatus* and *F. crotonensis* may be stressed. Inevitable, other factors such as meteorology and tides play a role in estuaries and phytoplankton growth, these factors were not considered in the laboratory. Despite daily variations of tides, the dam will not alter these variations. While our study was conducted in a laboratory, results corroborate other *in situ* experiments conducted around the world. In Portugal's Douro estuary, downstream of a hydroelectric dam, researchers determined a decaying exponential relationship between phytoplankton primary productivity and river flow, measured though chlorophyll *a* extraction and ^{14}C analysis (Azevedo et al., 2008). In Australia, phytoplankton biomass decreased as salinity increased and was instead replaced by an increase in benthic production (Segal et al., 2006). As Neu (1976) reported, increasing salinity has been noted in the spring over the last century along the entire length of the Gulf of Saint-Lawrence, and as far away as Halifax, as a result of hydroelectric dams on Quebec rivers. Furthermore, in the case of the Sainte-Marguerite River on Quebec's North Shore, a hydroelectric dam decreased the area of influence of the river plume, resulting in a decrease in primary productivity during the spring floods of May and June (Chapter III). Inevitably, the effect of increasing salinity is already occurring throughout the Saint-Lawrence watershed, and remains to be observed *in situ* in the Romaine River estuary.

2.5 Conclusion

Freshwater flow is one of the most important factors influencing estuary ecosystems. In northern settings, as freshwater flow is reduced, salinity increases in an estuary and water temperature decreases. Salinity and temperature play an important role in phytoplankton growth and photosynthesis. In the case of *A. falcatus* and *F. crotonensis* growth rate decreases as salinity increases. Furthermore, there exists an interaction between salinity and temperature, as growth rate is not affected in the same manner for both species at 15, 12 and 9°C. The photosynthetic apparatus for both species was damaged by increasing salinity, demonstrated by a decrease in Φ'_M, indicating that salinity acts as a toxicant. That temperature and salinity can have such a dominant effect on phytoplankton production is of particular importance because of the scale of changes that are taking place regarding freshwater flow. It is important to consider the cumulative affects that large-scale hydroelectric dams may have on phytoplankton communities in the coastal regions of the Gulf of St-Lawrence. Based on our laboratory results, we can suppose that dams on the Romaine River will alter phytoplankton growth in the estuary.

Acknowledgments

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TABLE AND FIGURES

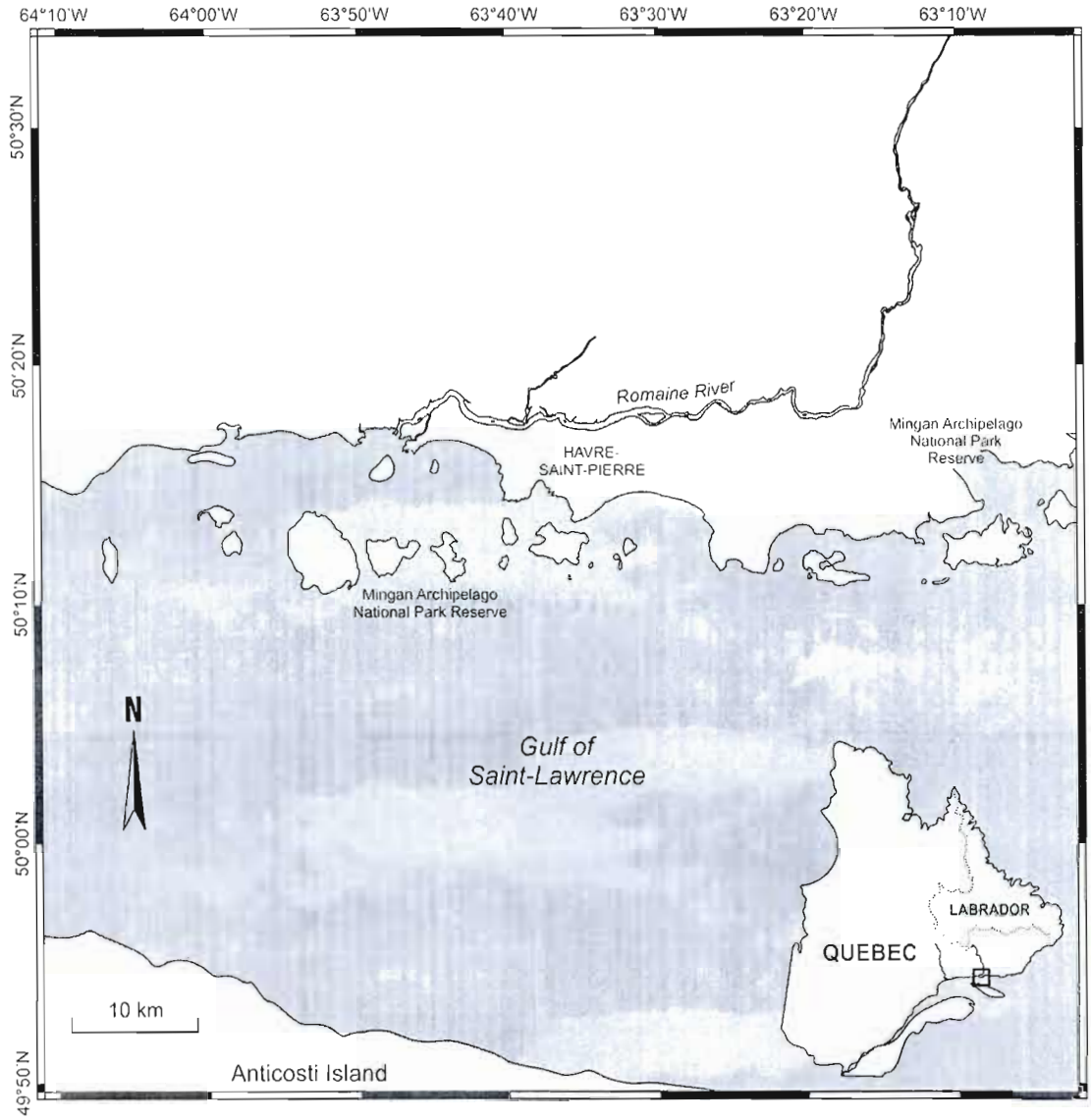

Figure 2.1: Romaine River and its estuary

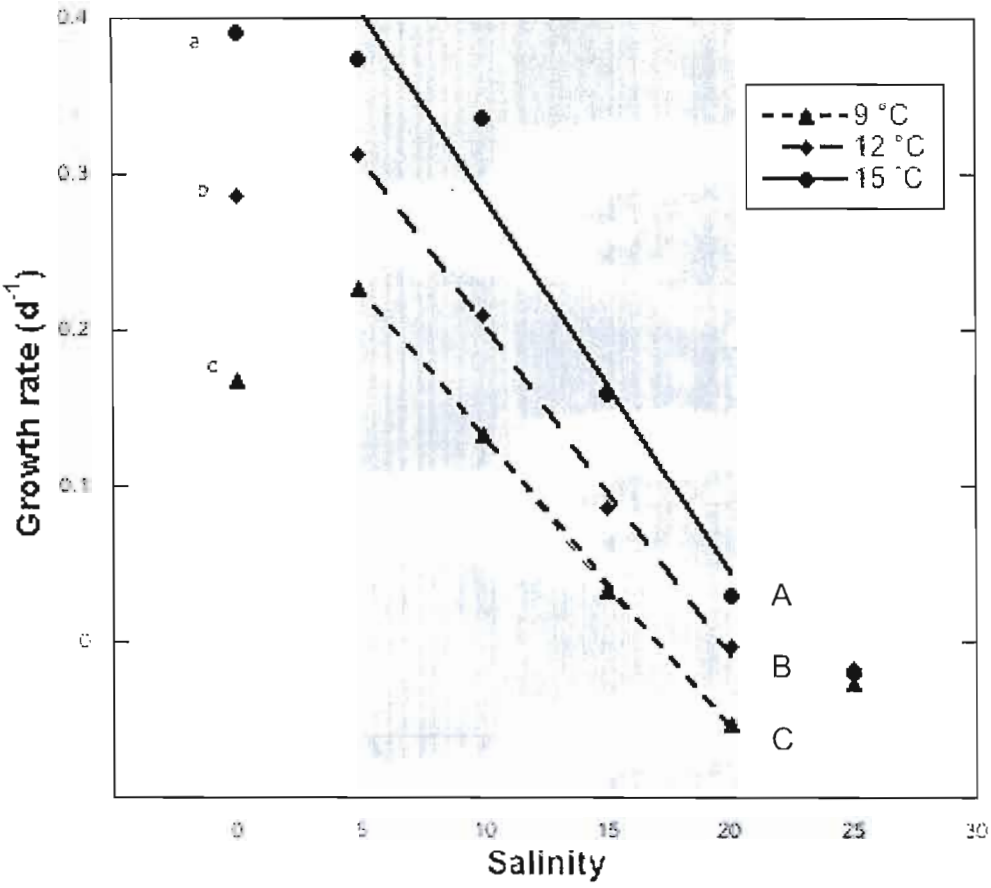

Figure 2.2: Growth rate for *A. falcatus* at 15, 12 and 9°C, exposed to a salt gradient over 72 hours. Salinity is displayed as parts per thousand. Tests were conducted on the shaded area, indicating the linear section of the curves.
[a,b,c] Tukey-Kramer test indicates that all starting points at salinity=0 are significantly different ($p<0.05$) from each other.
[A,B] Indicates a significant difference ($p<0.05$) between slopes

Table 2.1

Regression analysis of growth rate (d^{-1}) vs salinity (parts per thousand) for *A. falcatus* and *F. crotonensis* at different temperatures over 72 hours

Species	Temperature (°C)	n	Regression	r^2	SE
A. falcatus	15	12	y=0.527±0.262-0.0241±0.00191x	0.941	0.0370
	12	12	y=0.420±0.0126-0.0215±0.000918x	0.982	0.0178
	9	12	y=0.320±0.00424-0.0188±0.00031x	0.997	0.006
F. crotonensis	15	17	y=0.0772±0.0289-0.0108±0.00201x	0.659	0.0680
	12	18	y=0.0992±0.0318-0.0200±0.0021x	0.850	0.0761
	9	18	y=0.118±0.0292-0.0239±0.00193x	0.905	0.0699

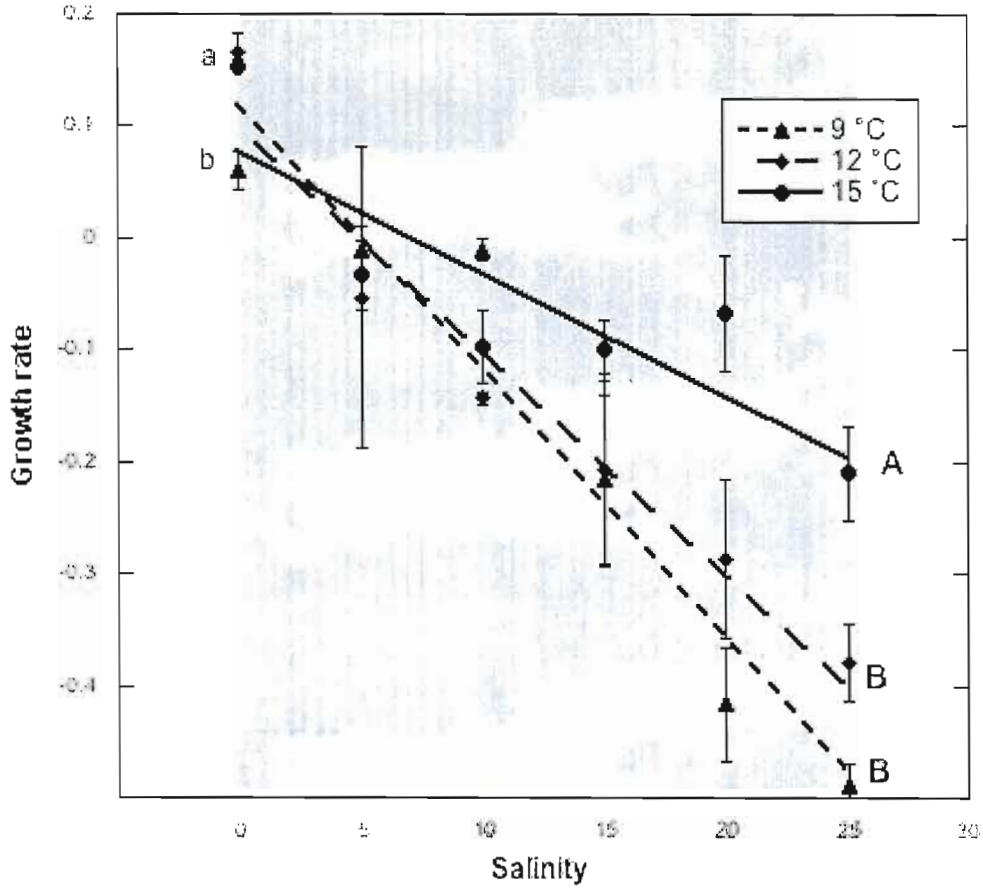

Figure 2.3: Growth rate for *F. crotonensis* at 15, 12 and 9°C, exposed to a salt gradient over 72 hours. Salinity is displayed as parts per thousand. Tests were conducted on the shaded area, indicating the linear section of the curves.
[a,b,] Tukey-Kramer test indicates that all starting points at salinity=0 are significantly different ($p<0.05$) from each other.
[A,B] Indicates a significant difference ($p<0.05$) between slopes

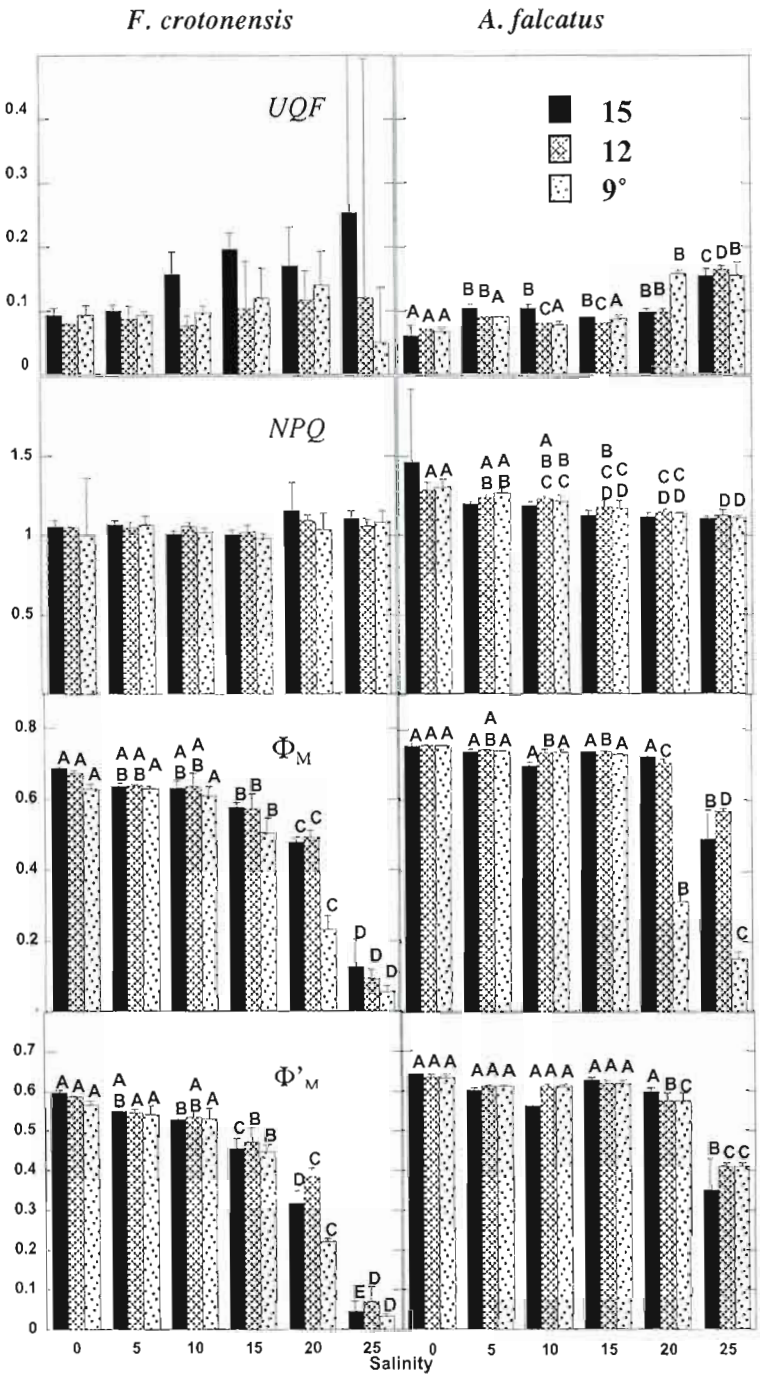

Figure 2.4: $UQF_{(REL)}$, NPQ, Φ_M and Φ'_M results for *F. crotonensis* and *A. falcatus* exposed to different concentrations of salt over 72 hours. Salinity is shown in parts per thousand. Capital letters indicate significant difference between parameters at differing salinities (n=3).

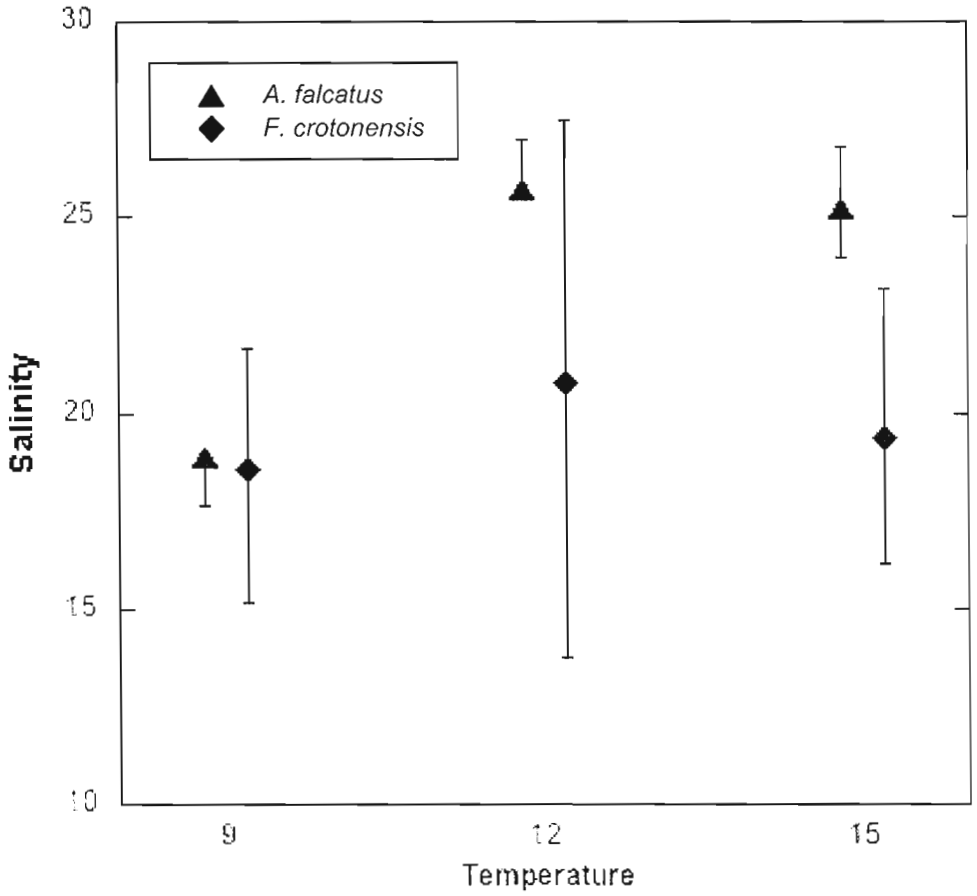

Figure 2.5: Φ'_M EC_{50} values for A. falcatus and F. crotonensis when exposed to salt (shown in parts per thousand) for 72 hours, with 95% confidence limits (where n=24).

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CHAPTER III

SCIENTIFIC ARTICLE

Using SeaWiFS data and Landsat-TM5 images to report changes in the physico-chemical variables of the Sainte-Marguerite River estuary, Quebec, before and after the construction of the Sainte-Marguerite 3 hydroelectric complex

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Abstract

Estuary ecosystems are largely influenced by freshwater discharge. Large-scale hydroelectric dams cause freshwater to reach estuaries at different times of the year and under different conditions. In Quebec a number of rivers are being dammed or diverted for hydroelectric production. A need exists to study the cumulative impacts of altered flow regimes on marine ecosystems, particularly how the physical and chemical properties of estuaries are altered downstream of hydroelectric dams. The Sainte-Marguerite Three (SM3) hydroelectric complex was built during the 1990's on the Sainte-Marguerite River, located near Sept-Iles on Quebec's North Shore. Using Landsat-TM5 maps and standard vertically generalized production model (VGPM) Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data, it was possible to map the river plume and estimate primary productivity in the estuary before and after the construction of the dam. A linear relationship exists between river flow and plume size, and a significant difference was noted between net primary productivity in the estuary before the dam was constructed compared to that after its construction. While results are limited by sample size, the information is startling as it hints that extensive large-scale repercussions of hydroelectric dams on rivers draining into the Gulf of Saint-Lawrence may already exist and may have altered the marine ecosystem.

Key Words: Sainte-Marguerite River, hydroelectricity, Landsat-TM5, SeaWiFS, primary production

3.1 Introduction

Estuary ecosystems are largely influenced by freshwater discharge. Large-scale hydroelectric dams cause freshwater to reach estuaries at different times of the year and under different conditions (Bunn and Arthington, 2002; Gough et al., 2005). In Quebec, hydroelectricity is the major source of energy and is becoming an increasingly important export for this Canadian province. As a result, more rivers are being dammed or diverted for hydroelectric production. A need exists to study the cumulative impacts of altered flow regimes on marine ecosystems, particularly how the physical and chemical properties of estuaries are altered downstream of hydroelectric dams.

The Sainte-Marguerite Three (SM3) hydroelectric complex was built during the 1990's on the Sainte-Marguerite River, located near Sept-Iles on Quebec's North Shore (Figure 3.1). Prior to the construction of the dam, it was estimated that the flow of the Sainte-Marguerite River during the spring floods of May and June was between 321.6m^3/s and 364m^3/s (Hydro-Québec, 1991). Hydro-Québec predicted that reservoir filling would start during May 1998 and would take up to 40 months. During this time, it was predicted that the flow of the Sainte-Marguerite River would be reduced to 20-35% of its original volume. Once the dams became operational, Hydro-Québec predicted that the flow would remain reduced, between 14 and 44% of its original volume during the biologically active period of the year (April to October). As a result, salinity in the estuary would increase and water temperature would decrease between April and October. According to Hydro-Québec's environmental impact assessment, the risk to primary productivity associated with the changes in the estuary was insignificant (1991). However, the environmental impact assessment did not measure the surface area of the river plume or how that region would be reduced when river flow decreased.

Along Quebec's North Shore, spring runoff from rivers normally occurs towards the end of May or the beginning of June. In the Gulf of St-Lawrence, higher inputs of freshwater lead to higher densities of phytoplankton, zooplankton and fish larvae in the Gulf of St-Lawrence (Sutcliffe, 1973; Grimes and Kingsford, 1996). Altering freshwater inflow changes the physical and chemical properties of an estuary by altering the interface between river and marine ecosystems (Sklar and Browder, 1998). As a result of decreasing freshwater inputs into marine ecosystems, marine salt water is able to encroach further upstream, resulting in higher than normal salinity concentrations and lower water temperatures in estuaries. In fact, it has been estimated that the Gulf of Saint-Lawrence exhibits higher than normal salinity levels during the spring because of the number of hydroelectric dams on rivers that flow into this body of water (Neu, 1976). According to Segal et al. (2006) and Azevedo et al. (2008), primary productivity in estuaries decreases with an increase in salinity. The studies, conducted *in situ*, demonstrated a decrease in chlorophyll *a* in samples collected along an increasing salinity gradient. A decrease in the ratio of photosynthesis to biomass was noted along an increasing salinity gradient, demonstrating that phytoplankton species show symptoms of stress when salinity increases (Segal et al., 2006). Salinity can act as a toxin for freshwater algae (Chapter II) and salinity has been suggested as one of the major constraints on species diversity and on the productivity of natural populations of algae in estuaries (Bartolomé et al., 2009).

In order to better understand what took place in the estuary of the Sainte-Marguerite River during the time of the spring run-off, Landsat-TM5 technology was used to map the estuary before and after the hydroelectric dam was built. Landsat-TM5 channel 6 provides thermal data, which can be calibrated to provide surface temperatures. River water is warmer than water from the Gulf of Saint-Lawrence and as a result it becomes possible to map the river plume based on water temperature. By selecting images captured by satellites from the middle of May to the middle of

June, it becomes possible to determine how the freshwater zone of influence decreased as a result of altered river flow.

Additionally, through the use of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data, primary production can be monitored before and after the construction of the dam to better understand how phytoplankton biomass in the estuary was affected by SM3. Primary production statistics were monitored for one year before the dam was constructed and for one year after the dam became operational and the reservoir had filled.

Other environmental factors will alter physical and chemical properties of an estuary such as weather and tides. The tidal prism, the difference in water volume between high and low tide, has a direct affect on estuarine salinity (Sklar and Browder, 1998). During the spring, when freshwater discharge is greatest, the influence of the tidal prism is lowest. Nevertheless, when possible, efforts were made to control for tides by comparing satellite images taken when tide levels were comparable.

By developing a better understanding of how the Sainte-Marguerite plume and the primary productivity in the estuary changed, it will become clearer what effects hydroelectric dams may have on estuarine ecosystems.

3.2 Methodology

3.2.1 Landsat-TM5

Landsat-TM5 maps were downloaded from the online archives at the United States Geographical Survey. Eleven maps were selected; seven dating from before the dam became operational and four after. Criteria for selection were low cloud

cover and images taken on dates during the spring when river runoff is traditionally higher (mid-May to early June). Additionally, seven images were chosen from the eleven for matched-pairs comparison. In order to be matched, time from high tide was calculated using Canadian tide and current tables from the Canadian Department of Fisheries and Oceans. Data were only compared for similar dates when time from high tide was within ten minutes from one map to the next. Using bandwidth 6, temperature calculations were conducted using GrassGIS 6.3.0-2 software (Construction Engineering Research Laboratory, Champaign, USA) according to Neteler and Mitasova (2008). A mask was created in order to eliminate land area and cloud cover from sea-surface water temperature calculations. Water temperature was calculated according to the following equation (Qin et al., 2001), where k_1 and K_2 are calibration constants (Chander and Markham, 2003):

$$T_B = T_{sensor} = \frac{K_2}{\ln(k_1/L_\lambda + 1)}$$

It is possible to map the plume of the Sainte-Marguerite River based on sea-surface temperature, because plumes appear warmer (Thibault et al., 2002) and can be identified using Landsat-TM5 images (Haakstad et al., 1994). Using QGIS 1.3.0 Mimas software, color maps were created based on sea-surface temperature and the surface areas of plumes, based on warmer temperatures, were calculated using shape files.

Dates of images were: May 14th, 1985; May 30th, 1985; June 5th, 1988; June 26th, 1989; May 12th, 1990; May 28th, 1990; June 16th, 1991; May 13th, 2002; May 8th, 2006; May 24th, 2006 and May 27th, 2007. For all images the satellite passed between 14:45 and 15:15. The reservoir began filling in May of 1998.

3.2.2 SeaWiFS

Standard vertically generalized production model (VGPM) SeaWiFS data was obtained from Ocean Productivity (Oregon State University, USA) and photosynthetic rates derived according to Behrenfeld and Falkowski (1997). Maps were downloaded for 1997-1998 and for 2006-2007; one year before and one after the SM3 dam became operational. Each map covered an 8-day period with a grid size of 2160 x 4320. Nine pixels were selected based on their geographical location at the area of the Sainte-Marguerite estuary (Figure 3.1) and named north-west (NW), north-center (NC), north-east (NE), center-west (CW), center-center (CC), center-east (CE), south-west (SW), south-center (SC) and south-east (SE) (Table 3.1). Maps were analyzed and milligrams of carbon data were collected using Quantum GIS Geographical Information System 1.3.0 Mimas software (Open Source Geospatial Foundation Project).

3.2.3 Statistics

A matched-pairs test was conducted for plume size, determined through Landsat imagery, before and after the dam was constructed. Additionally, a linear regression analysis was calculated to determine the relationship between river flow and plume size. River flow data was provided by Hydro-Québec (2010).

Primary production statistics were determined using carbon data obtained through SeaWiFS. Unilateral matched-pairs t-tests were conducted for each point between the two years using the hypothesis 2006-2007 < 1997-1998 where $p<0.05$. It was then decided to do a combining probabilities from tests of significance, which was conducted for all pairs using the formula $-2\sum \ln P$ outlined by Fisher (1954), because of a tendency towards the hypothesis for all points. Accordingly, if all experiments were true, or tended towards the hypothesis, the quantity would be distributed by x2 with 2k degrees of freedom (where k=the number of separate tests and probabilities). In this case, k=9.

Statistical analysis was done using JMP 7.0.1 software (Cary, NC, USA) and figures are presented using KaleidaGraph 4.1 (Synergy Software, Reading, PA, USA).

3.3 Results

3.3.1 Landsat-5

Using Landsat-5 imagery it was possible to note the difference in size of the fresh water plume before and after the dam was constructed. Using a matched-pairs test, it was determined that the average plume size during the mid-May to early June period before the dam was constructed was 36.9km^2 and 2.63km^2 after the dam was constructed, where $p>0.1003$. The results are not significantly different, likely because of a smalll number of samples ($n=4$). The number of images available during the spring floods limited sample size, as did the ability to match pairs based on similar time tide levels.

From the Landsat-TM5 satellite images, a linear relationship was found to exist between river flow (m^3/s) and the size of the Sainte-Marguerite plume (km^2) (Figure 3.2) between mid-May and early June. As river discharge decreased, surface area (km^2) of the plume also decreased, where $y=-1.3706\pm6.107 + 0.14018\pm0.02704x$, with a standard error of 13.592. While the relationship is highly significant ($p>0.0006$), the high error is likely related to a limited sample size ($n=11$).

3.3.2 SeaWiFS

A significant difference was noted between the years 1997-1998 and 2006-2007 for the period of mid-May to early June for the points CW, SW, SC and SE, where the probability that 1997-98 was greater than 2006-07 was 0.0204, 0.0284, 0.0032 and 0.0023 respectively (Figure 3.3). A tendency towards the hypothesis for

the overall differences between 1997-98 and 2006-07 was noted, in that each point noted higher primary productivity in 1997-1998 than 2006-2007.

The value of $-2\sum \ln P$ is greater than $\chi^2.01(18)= 34.81$, it can be concluded that there was a highly significant difference between primary productivity measured before the dam was constructed compared to that after the dam was constructed (Figure 3.3).

3.4 Discussion

Studies have demonstrated that higher inputs of freshwater into marine ecosystems correlate with higher densities of phytoplankton, zooplankton and fish larvae (Sutcliffe, 1973; Grimes and Kingsford, 1996). Therefore, it was important that Landsat-TM5 images be selected during the spring flood, from mid-May to early June, when river discharge is highest and a greater difference would be noted. Due to limited sample size, it is difficult to confirm results. Additional limitations exist in that, because of the fairly recent construction of the SM3 hydroelectric complex, fewer images, taken since the dam became operational, were available for analysis. Nevertheless, the relationship between river runoff and plume size provides important insights. Altering plume size during the spring will have significant repercussions for biological activity in the coastal zones of the Gulf throughout the growing season. In the spring, river plumes in the Gulf of Saint-Lawrence provide ideal growing conditions for phytoplankton. The frontal zones between river and ocean waters are high in nutrients from river discharge and from upwelling, and are areas with high rates of primary productivity (Grimes and Kingsford, 1996). High inputs of freshwater often correlate with high rates of phytoplankton productivity and influence zooplankton and fish larvae production (Sutcliffe, 1973; Grimes and Kingsford, 1996).

Freshwater inflow is one of the most important factors affecting phytoplankton community structure and function in estuaries (Chapter II; Sklar and Browder, 1998). As freshwater inputs decrease, so too does the zone of influence. According to our results, there was a marked direct relationship between river discharge and plume surface area. It is important to note that tides also greatly affect plume size, in that when the flow from the Sainte-Marguerite River was moderate, a high tide can alter the size of the plume, as seen for the point on the graph where flow was $220m^3/s$ but the surface area was less than $10km^2$. This point was the only point with a moderate flow when the image was captured at high tide.

According to the Sainte-Marguerite environmental impact assessment, primary productivity would be greater after the dam became operational than before (Hydro-Québec, 1991). Our results from analysis of SeaWiFS data do not support these predictions. Although data were again limited by sample size, a significant difference was noted between primary production before and after the construction of the dam for the ensemble of sampled points throughout the entire year. A greater difference was noted between phytoplankton biomass for the points CW, SW, SC and SE; which is in line with Landsat-TM5 findings, indicating the size of the zone of freshwater influence decreased. Likely, these points would no longer be affected by freshwater inputs, leading to an increase in salinity. Salinity has been suggested as a major constraint on diversity in estuaries (Sklar and Browder, 1998) and phytoplankton productivity (Bartolomé et al., 2009). Both freshwater species and salt-water species can benefit from lower salinities, enabling richer phytoplankton communities (Chapter II; Chan and Hamilton, 2001; Weise et al., 2002). While marine phytoplankton are adapted to high salinity levels, species such as *Alexandrium Tamarense* demonstrate greater growth rates at slightly lower salinities, less than 24 parts per thousand, and are found in higher abundance near river plumes (Weise et al., 2002). In the case of freshwater species, a marked decrease in growth rate was

noted for *Ankistrodesmus falcatus* and *Fragilaria crotonensis* when salinity increased and photosynthesis was affected (Chapter 2). Phytoplankton growth may also be affected by additional factors caused by decreasing river runoff, such as nutrient availability, turbidity and mixing (Hydro-Québec, 2007).

The use of SeaWiFS data provided an interesting and accessible tool for gauging changes that have occurred in the Sainte-Marguerite estuary in terms of overall carbon content. Due to the recent introduction of the satellite technology, only one year of data exists from before the dams became operational. While the technique is interesting, the results remain limited by little available data. It is difficult to make generalizations based on only two years of available data, as other factors play important roles in primary production. Nevertheless a marked difference was noted between primary production in the area of study prior to the dam and after the dam.

3.5 Conclusion

Our results corroborate with other studies indicating that in the Gulf of Saint Lawrence, river plumes and estuaries greatly influence phytoplankton communities. As freshwater inputs alter, the interface between river and marine ecosystems shifts, which therefore creates smaller plumes. As a result, phytoplankton biomass decreases, which may have serious repercussions for estuarine ecosystems. While it is necessary to verify results with *in situ* studies, initial findings justify a need for more monitoring of environmental changes resulting from hydroelectric dams.

All data and programs used for the purpose of this study are open source and free to the public. A conscious decision was made to use only technologies available to the public in order to demonstrate a method for free and open surveillance of large-scale developments, which could be used by non-governmental organizations or concerned citizens. Overtime, it will be possible to more accurately monitor changes

to the Sainte-Marguerite estuary, as well as other estuaries affected by hydroelectric dams, using these technologies.

TABLES AND FIGURES

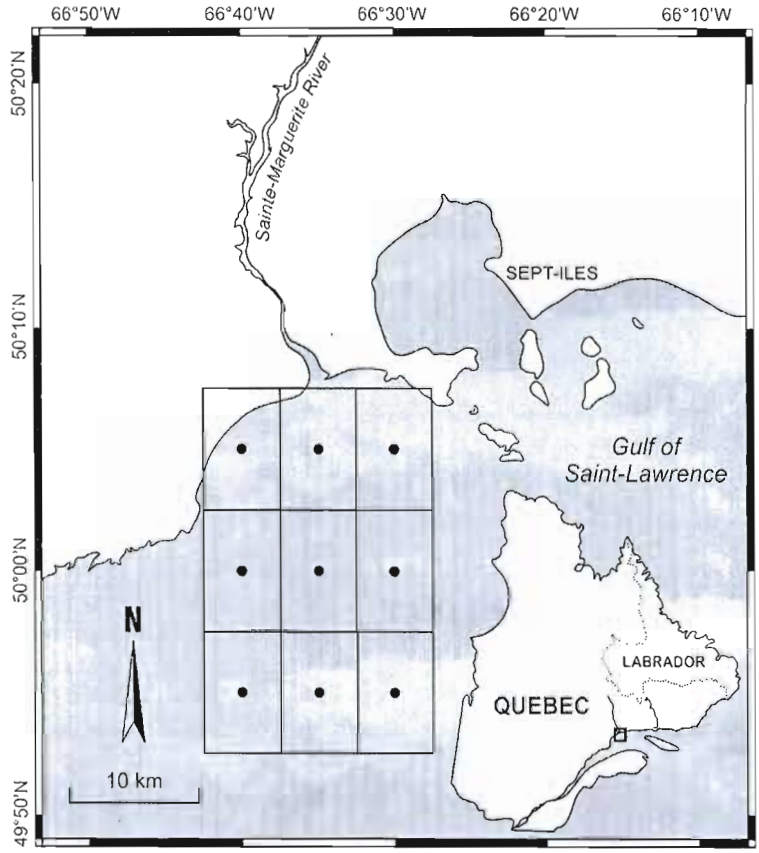

Figure 3.1: Sainte-Marguerite River and its estuary
*Grid marks individual pixels of SeaWiFS data

Table 3.1
Latitude and longitude for each of the nine SeaWiFS points

North-west	**North-center**	**North-east**
50°05'00.00"N	50°05'00.00"N	50°05'00.00"N
66°40'00.00"W	66°35'00.00"W	66°30'00.00"W
Center-west	**Center-center**	**Center-east**
50°00'00.00"N	50°00'00.00"N	50°00'00.00"N
66°40'00.00"W	66°35'00.00"W	66°30'00.00"W
South-west	**South-center**	**South-east**
49°55'00.00"N	49°55'00.00"N	49°55'00.00"N
66°40'00.00"W	66°35'00.00"W	66°30'00.00"W

* Site selection was made based on proximity to Sainte-Marguerite River and confined by SeaWiFS pixels.

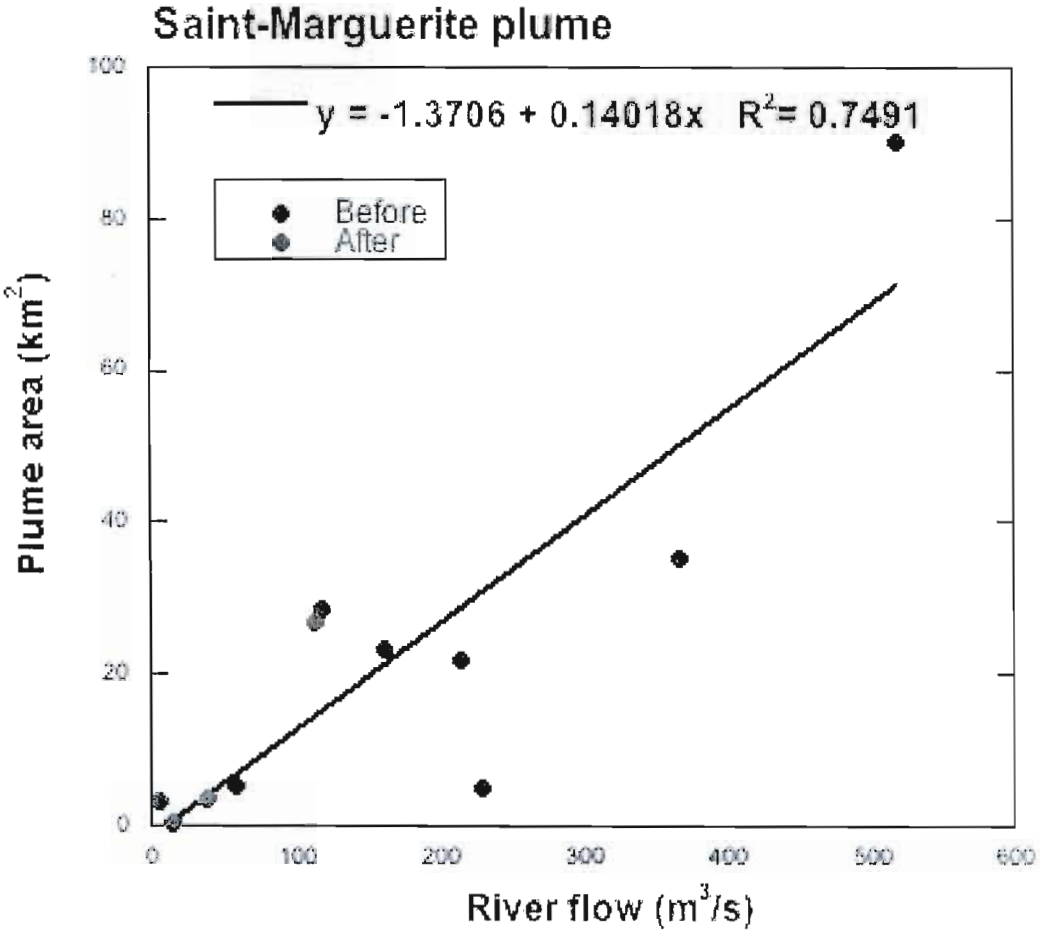

Figure 3.2: Relationship between plume area and river flow for the Sainte-Marguerite estuary between mid-May and early June, before and after the construction of the SM3 hydroelectric complex, where n=11 and p>0.0006.

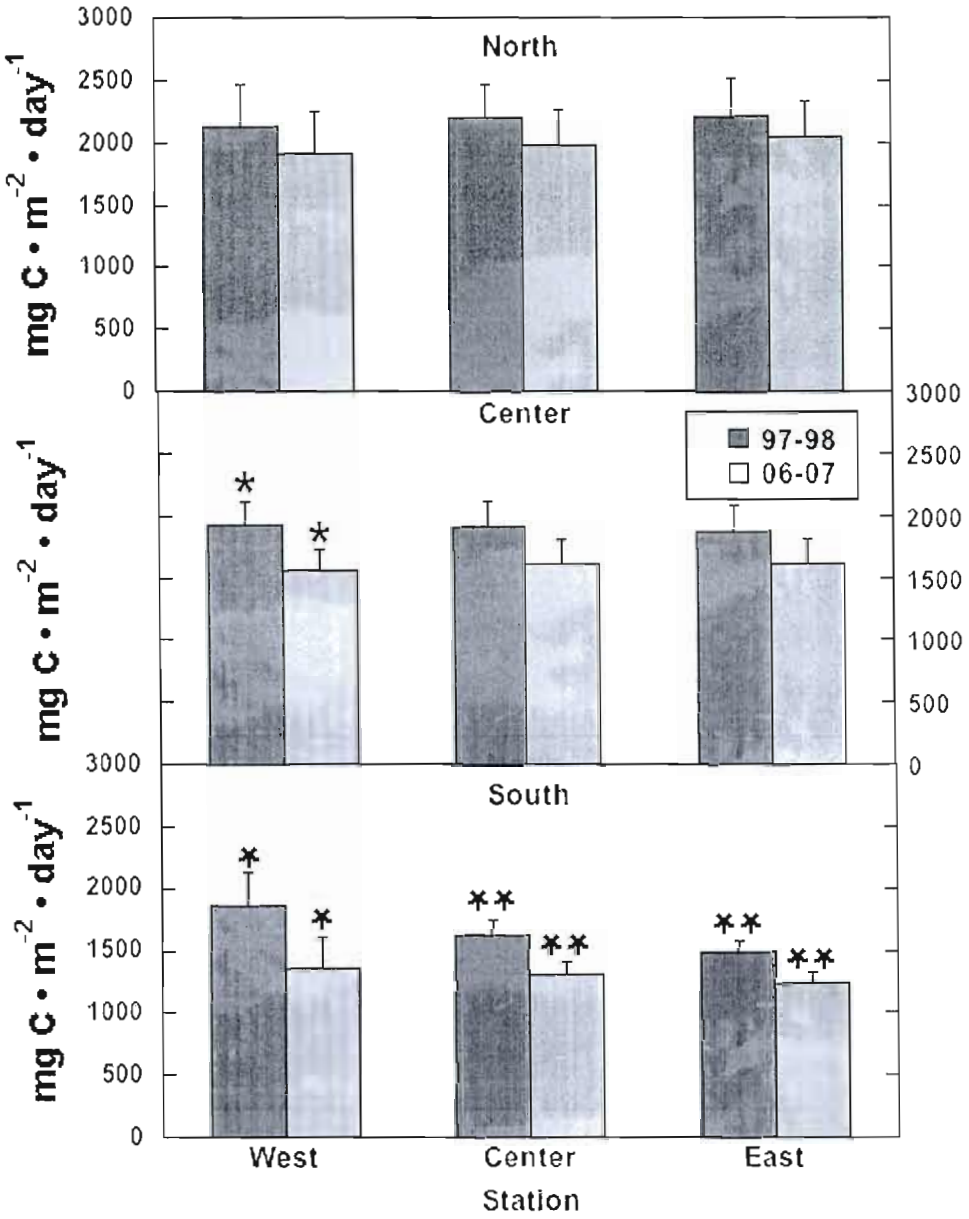

Figure 3.3: Average primary production for nine stations from 1997-1998 and 2006-2007. The symbol * indicates significant differences ($p<0.05$) and ** indicates very significant differences ($p<0.01$). A tendency towards the hypothesis is noted for all stations.

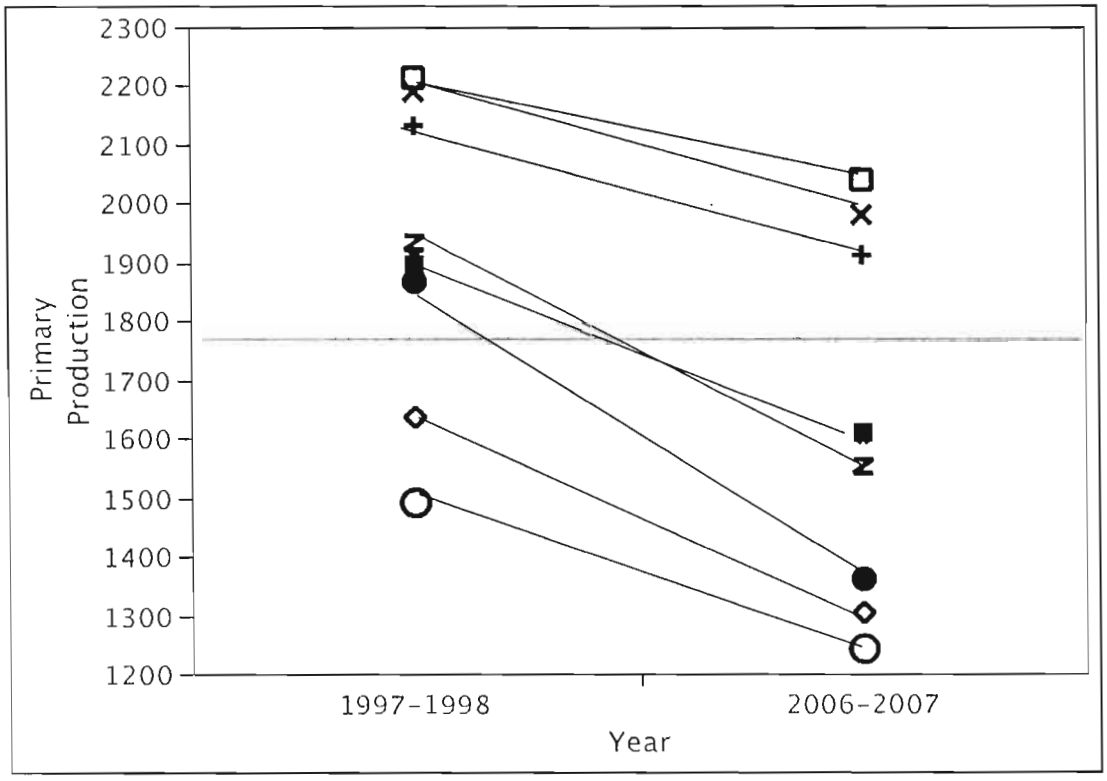

Figure 3.4: Average primary production ($mgC \cdot m^{-2} \cdot day^{-1}$) for each station in 1997-1998 in comparison with 2006-2007 for the Mid-May to early June period. Tendency towards the hypothesis is noted where $p>0.005$, $n=9$.

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CHAPITRE IV

GENERAL CONLCUSION

With the combined use of laboratory studies and satellite images it was possible to gain a better understanding of how hydroelectric dams may alter marine ecosystems. While our research focused on changes in water temperature and salinity and how these changes in the physical and chemical properties of an estuary may affect phytoplankton growth, our results enable us to ask more questions and formulate new hypotheses.

4.1 Résumé of principal results

In the case of the laboratory study, initial results indicate that phytoplankton species do not react in the same fashion to increasing salinity. Although both *A. falcatus* and *F. crotonensis* exhibited decreasing growth rates as salinity increased, *A. falcatus* was more sensitive to salt as its growth rate decreased more drastically at lower salinities.

Temperature also affected growth rate, although again not evenly for each species. As temperature decreased, so too did growth rate. Interestingly, there appeared to be an interaction between salinity and temperature as growth rate was affected differently. *A. falcatus* was more affected by an increase in salinity at 15°C than at 12 and 9°C, which was shown by a higher slope for the regression analysis of growth rate versus salinity. In contrast, *F. crotonensis* was more affected by an increasing salinity at 9°C than at 12 and 15°C.

In addition to growth rate, photosynthesis of both species was also affected by increasing salinity, which was shown by changes to Φ'_M. EC50 values ranged from 18.8 to 25.7 parts per thousand for *A. falcatus* and from 18.6 to 19.4 for *F.*

crotonensis. Salinity affects photosynthesis and can act as a toxin to the photosynthetic apparatus of these two phytoplankton species.

In the case of the Sainte-Marguerite River, a linear relationship exists between the volume of water reaching the estuary and the size of the river plume. Additionally, a significant difference was noted between primary production in the year prior to construction of the Sainte-Marguerite 3 hydroelectric complex than post construction. For all nine points examined with SeaWiFS data, the quantity of carbon measured was larger in the year prior to construction.

4.2 New perspectives

Over the course of this research new questions have emerged with regards to salt toxicity as well as interactions between salinity and temperature and their effects on phytoplankton growth. Furthermore, greater questions emerged regarding the overall affect of hydroelectric dams on marine ecosystems.

Interestingly, when phytoplankton were grown under laboratory conditions their growth rate appeared to be affected at lower salt concentrations than photosynthesis. Furthermore, growth rates were affected differently for all species at different temperatures, demonstrating an interaction between salinity and water temperature. Further laboratory studies are necessary in order to better understand how salt affects the photosynthetic apparatus of algae and why growth rate may be affected first.

A concerted effort was made in the case of satellite images to only use images and software that are open access and free to the public. This conscious decision was made so that the technique of examining the consequences of large-scale hydroelectric dams could be used by environmental organizations with limited budgets. While the technique provided interesting insights, it was limited because of

the recent introduction of the SeaWiFS technology and limited information on river flows. It would be interesting to further pursue results obtained with Landsat-TM5 images and SeaWiFS data. To do so, it would be important to have more in-depth knowledge of daily river flow.

Estuaries have rich and diverse ecosystems that are made possible in large part due to healthy phytoplankton communities. Currently in Quebec, it is not mandatory for the proponents of hydroelectric developments to study the cumulative impacts of multiple dams on a single watershed. It is necessary to further our understanding of the effect that hydroelectric dams have on estuarine phytoplankton communities in order to understand the repercussions of extensive large-scale hydroelectric development.

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